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ALTITUDE DEPENDENCE OF C_T^2 OVER THE OCEAN

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and

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The height dependence of the temperature structure parameter, C_T^2, has been measured with microthermal sensors mounted on a light aircraft. This work was done in conjunction with optical propagation and turbulent transport research in the marine boundary layer. These measurements indicate that, in the absence of a strong inversion, the constant stress layer can be surprisingly thin. The measurements also substantiate the strong role played by temperature and water vapor discontinuities in turbulence above the boundary layer.

ALTITUDE DEPENDENCE OF C_T^2 OVER THE OCEAN

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ABSTRACT

The height dependence of the temperature structure parameter, C_T^2, has been measured with microthermal sensors mounted on a light aircraft. This work was done in conjunction with optical propagation and turbulent transport research in the marine boundary layer. These measurements indicate that, in the absence of a strong inversion, the constant stress layer can be surprisingly thin. The measurements also substantiate the strong role played by temperature and water vapor discontinuities in turbulence above the boundary layer.

ALTITUDE DEPENDENCE OF ATMOSPHERIC TURBULENCE OVER THE OCEAN

I. INTRODUCTION

We have made measurements of temperature structure parameter, C_T^2, from a light aircraft using microthermal sensors as part of a study of turbulence in the marine boundary layer. C_T^2 is important for optical propagation studies due to its relation to the index of refraction structure parameter, C_N^2, [Friehe (1977)]

$$C_N^2 = (79 \times 10^{-6} P/T^2)^2 \, (C_T^2 + .11\, C_{Tq} + 3.2 \times 10^{-3} C_q^2) \tag{1}$$

where: C_q^2 is the water vapor structure parameter,

C_{Tq} is the cospectrum structure parameter,

p is the pressure in mb, and

T is the absolute temperature.

The water vapor fluctuations are usually relatively small so we can write

$$C_N^2 = (79 \times 10^{-6} P/T^2)^2 \, C_T^2 \tag{2}$$

This relationship is shown in Fig. 1 with C_N^2/C_T^2 as a function of altitude for the U.S. Standard Atmosphere. Turbulence is also of interest because of the role of eddy diffusion in the transport of heat, water vapor, and pollutants. These factors are important in the formation of marine fog and air pollution modeling.

Only a few measurements of the altitude dependence of C_T^2 have been made to date. Korpov and Tsvang (1966) have made measurements of C_T^2 with an acoustic anemometer on an airplane and have related their results to the vertical temperature gradient. Microthermal sensors have been used to measure C_T^2 with balloon borne equipment by Bufton (1973) and airplane borne equipment

by Lawrence (1970) and Collins (1977). Recently, Hanson (1976) has combined airplane microthermal measurements and remote scintillometer determinations of C_N^2 and compared his results with an impirical model developed by Yura. Based on this body of data, Hall (1977) has compiled a conglomerate curve of C_T^2 as a function of altitude (Fig. 2) for daytime overland data. Only Ochs (1973) has reported measurements over the ocean.

The data we are reporting on were taken as part of three separate research operations. The first was the "Cooperative Experiment for West Coast Oceanography and Meteorology - 1976" (designated CEWCOM 76), a marine fog research project off San Diego. CEWCOM 76 was organized by the Naval Postgraduate School and the Naval Electronics Laboratory Center. The second was a marine fog and aerosol project in the Gulf of Mexico off Panama City, Florida (designated FLORIDA 77). The third was in conjunction with a turbulence and aerosol research cruise on the USNS Hayes in the Atlantic (designated HAYES 77) organized by the Naval Research Laboratory.

II. INSTRUMENTATION AND TECHNIQUES

The platform for our measurements is a single engine turbocharged Bellanca operated by Airborne Research Associates (Fig. 3). This aircraft has been flown as low as 3 meters and as high as 10,000 meters and makes an excellent tool for the low altitude flights required for boundary layer research. The aircraft is well instrumented, allowing simultaneous measurements of air temperature, altitude, dew point, electric field, visibility, infrared surface temperature, and microwave refractive index. The data is normally recorded with an eight channel strip chart recorder.

The temperature structure parameter is measured using the paired sensor method. Given two temperature sensors, 1 and 2, a distance d apart, then [Lumley (1964)]

$$C_T^2 = \langle (T_2 - T_1)^2 \rangle d^{-2/3} \tag{3}$$

This quantity is related to the Kolmogorov power spectral density of temperature fluctuations, $\phi_T(k)$,

$$\phi_T(k) = .25\, C_T^2\, k^{-5/3} \tag{4}$$

where k is the wave number. Equation 4 applies in the inertial subrange part of the spectrum where the turbulence is nearly isotropic, allowing a one-dimensional representation of $\phi_T(k)$. C_T^2 is independent of d in the inertial subrange.

The device we have used to measure C_T^2 is a DC Wheatstone bridge (Thermo Systems Model 1044) that senses the relative resistance fluctuations of a

pair of 2.5 micron diameter platinum wires separated by about one meter. The sensors were originally mounted on the leading edge of the wing (CEWCOM 76 and FLORIDA 77) but the noise level was very high so the sensors were moved to the present wing tip location (Fig. 4). The output of the bridge (proportional to $\Delta T = T_2 - T_1$) is processed by an RMS module with a 5 sec time constant and recorded on the strip chart recorder as ΔT_{RMS}. The sensitivity is limited by the broad band noise of the system due to inherent amplifier noise and pickup from the aircraft ignition system. For CEWCOM 76 and FLORIDA 77 the noise level corresponds to $C_T^2 \sim 4 \times 10^{-4}$ $k^2/m^{2/3}$, for HAYES 77 the noise level is lower ($C_T^2 \sim 10^{-4}\ k^2/m^{2/3}$) since we were using the wing tip probe configuration. It is possible to improve the accuracy by correcting for the noise. If we assume an RMS noise level of N, then the noise correction appears as

$$C_T^2 = [\ (\Delta T_{RMS})^2 - N^2\ ]\ d^{-2/3} \qquad (5)$$

Since 2.5 micron wires are fragile, breakage is a continual problem. Except for one bad batch of wires, we have found a typical lifetime of one or two flights for a given wire. We presently have two pairs of sensors mounted and can switch to a good pair if one wire breaks.

III. THEORY

The boundary layer is that part of the atmosphere where friction with and heating by the surface play an important part in the generation of turbulence. Near the surface the shear stress and scalar fluxes are essentially constant. In this region the fluxes can be represented by scaling parameters (such as U_* and T_*) that are independent of height. We shall refer to this layer of nearly constant stress and flux as the surface layer. In the surface layer, the height above the surface, Z, is the appropriate turbulence length parameter. For a complete treatment of the surface layer equations we suggest Lumely (1964), Businger (1971) or Kraus (1972). The normalized momentum flux, F_m, and the normalized heat flux, F_h, for turbulent transport are

$$F_m = - < u'w' > = U_*^2 \tag{6}$$

$$F_h = - < T'w' > = U_* T_* \tag{7}$$

where u' is the horizontal velocity fluctuations,

w' is the vertical velocity fluctuations,

T' is the temperature fluctuations,

U_* is the friction velocity, and

T_* is the scaling temperature.

The atmospheric stability is represented by either the Monin-Obukov length, L, or the Richardson number, R_i,

$$L = \frac{T\ U_*^2}{KgT_{v*}} \tag{8}$$

$$R_i = \frac{g(\partial T_V/\partial Z)}{T(\partial U/\partial Z)^2} \tag{9}$$

where T_V is the virtual potential temperature,

g is the acceleration of gravity,

U is the mean horizontal velocity, and

$K = .35$ is the Von Karmon constant.

The mean and fluctuating temperature dependences on height are given by [Wyngaard (1971)]

$$\frac{\partial T}{\partial Z} = \frac{T_*}{KZ} f_1 (Z/L) \tag{10}$$

$$C_T^2 = T_*^2 Z^{-2/3} f_2 (Z/L) \tag{11}$$

Under near-neutral conditions f_1 and f_2 are equal to unity, resulting in a logarithmic mean temperature profile and C_T^2 proportional to $Z^{-2/3}$. Under unstable conditions ($- Z/L >> 1/7$) C_T^2 is proportional to $Z^{-4/3}$. These relationships are based on measurements made on a flat Kansas plain with averaging times of about one hour. Due to the shorter average time involved in aircraft profiles, one expects scatter about the curve of Eq. 11 even in the surface layer.

Wyngaard points out that although these results are based on surface measurements ($Z < 22$ m) they are valid to somewhat greater heights. In the case of the well developed unstable boundary layer, the predicted C_T^2 profile is valid well beyond the surface layer. Although Davidson (1977) has found evidence of wave influence restrictions on the lower limit of

the oceanic surface layer equations, the primary interest of optics and transport users is in establishing the upper limits of validity.

The upper limit is often assumed to be at least half the distance to the first inversion. This distinction becomes even more tenuous if there is no low inversion. Above the surface layer, equations 10 and 11 become meaningless when defined in terms of the absolute height above the surface, Z. Since the vertical gradients are still meaningful, Richardson number remains a useful representation of stability. The appropriate length parameter is the integral scale (or outer scale), Λ, which is a measure of the largest size (or minimum wave number) for which the Kolmogorov spectrum of equation 4 is valid [Hinze (1959)]. In the surface layer Λ is proportional to Z. In this representation we have

$$\frac{\partial T}{\partial Z} = \frac{T_*}{K' \Lambda_T} f_1' \, (R_i) \tag{12}$$

$$C_T^{\,2} = T_*^{\,2} \, (\Lambda_T)^{-2/3} \, f_2' \, (R_i) \tag{13}$$

where f_1' and f_2' are analogous to f_1 and f_2.

IV. RESULTS

Shipboard and platform measurements of C_T^2 have shown fairly good agreement with the predicted height dependence in the near surface layer ($Z < 25$ meters). Fig. 5 shows a profile taken at the Naval Coastal Systems Laboratory's Stage I in the Gulf of Mexico during FLORIDA 77. We have found the marine surface layer to be predominately near-neutral with a tendency to be slightly unstable. Based on numerous shipboard measurements we have found typical values of $L \cong -100$ meters and $T_* \cong -.08$ °C. Using these values we have indicated typical surface based C_T^2 profile (from equation 11) as the dashed line in Fig. 2. Under these conditions we would expect $C_T^2 \sim Z^{-4/3}$ to be a good approximation for $Z \gtrsim 20$ meters. However, during HAYES 77 we found the Atlantic Coast from Cape Code to Newfoundland to have a stable surface layer. It has been our experience from various shipboard operations that stable conditions are most likely to produce anomalous C_T^2 profiles in the near surface layer.

The surface layer is usually well defined off the Pacific Coast of the United States due to the persistence of a strong marine inversion. Consequently, we can expect C_T^2 to be well described by the $Z^{-2/3}$ or $Z^{-4/3}$ equation. In Fig. 6 we have two aircraft measurements of C_T^2 before and after a radiosonde balloon launch during near neutral conditions. The C_T^2 profile is very well fit by the $Z^{-2/3}$ law until the inversion is reached, where C_T^2 increases rapidly with the temperature gradient. In this case the surface layer dominates the entire boundary layer. The strong peak in C_T^2 at the inversion ($Z \sim 200$ m) is in agreement with the ship's acoustic sounder.

The Atlantic Coast data taken during HAYES 77 is considerably less encouraging. In Fig. 7 we can see a well developed surface layer similar

to the Pacific Coast profile of Fig. 6. The marine inversion occurs at $Z \cong 200$ meters. There is also a strong layer of turbulence which occurs above a sharp temperature discontinuity at $Z \cong 1700$ meters. In Fig. 8 the well defined surface layer extends only as high as $Z \cong 30$ meters. Note the strong peaks in C_T^2 which occur at the dew point discontinuities, indicating the importance of water vapor in atmospheric stability. In Fig. 9 we find very low levels of temperature turbulence above the inversion, but below the inversion the values of C_T^2 are very large considering that these are stable conditions. Figs. 10 and 11 show low values of C_T^2 near the surface with C_T^2 increasing with height as we approach maximum temperature at $Z \cong 400$ meters. In this case, the normal surface layer equations are a very poor representation. It is also interesting to note that a nearby profile (Fig. 12, taken about 100 km south of those shown in Figs. 10 and 11) is completely different.

V. CONCLUSIONS

In the presence of a raised marine inversion, such as off the Pacific Coast, a well mixed turbulent boundary layer is usually found. The height dependence of C_T^2 in this layer will be well described by the standard surface layer expressions up to the inversion. In the absence of a strong raised inversion, such as is often the case off the Atlantic Coast, there may be no well mixed turbulent boundary layer. This is particularly true under stable conditions where the magnitude of C_T^2 found at the surface may in fact be dominated by a low level temperature discontinuity. Under these conditions, the standard surface layer equations may be invalid above heights on the order of 10 meters.

Above the boundary layer, air mass boundaries and other sources of temperature, velocity, and water vapor discontinuities play a critical role in the magnitude of C_T^2. This is even more significant for optical propagation because C_N^2 is also affected by water vapor fluctuations (eq. 1). A profile taken during FLORIDA 77 (Fig. 13) shows that these layers can produce large effects as high as 5,000 meters.

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FIGURE CAPTIONS

1. Height dependence of C_N^2/C_T^2 based on eq. 2 for the U.S. Standard Atmosphere.

2. Height dependence of C_T^2. The solid line is the ground average compiled by Hall (1977) for daytime overland profiles. The dashed line is an extrapolation using eq. 11 from typical shipboard oceanic surface layer measurements.

3. Airborne Research Associates, Inc., Bellanca research aircraft during operations off Nova Scotia with the USNS Hayes in May of 1977.

4. Wingtip probe configuration for measurement of C_T^2.

5. Height dependence of C_T^2 measured from the Naval Coastal Systems Laboratory Stage I off Panama City, Florida during FLORIDA 77.

6. Height dependence of C_T^2 for two profiles during CEWCOM 76 with a simultaneous ship launched radiosonde.

7. Temperature and C_T^2 profiles off the New Jersey Coast, 22 Feb. 1977. The top of the haze layer was 1700 meters.

8. Temperature,dewpoint and C_T^2 profile (HAYES 77) near the Nantucket Light Ship on 16 May 1977 at 1325 ADST.

9. Temperature, dewpoint and C_T^2 profile (HAYES 77) near Cape Sable, N.S. on 17 May 1977 at 1525 ADST. The x's denote C_T^2 values and the arrow denotes the ocean temperature measured from the USNS Hayes.

10. Temperature, dewpoint and C_T^2 profile (HAYES 77) about 20 km east of Cape Canso, N.S. on 18 May 1977 at 1625 ADST. The x's denote C_T^2 values and the arrow denotes the ocean temperature measured from the USNS Hayes.

11. Temperature, dewpoint and C_T^2 profile (HAYES 77) about 20 km east of Cape Canso, N.S. on 18 May 1977 at 1715 ADST. The x's denote C_T^2 values and the arrow denotes the ocean temperature measured from the USNS Hayes.

12. Temperature, dewpoint and C_T^2 profile (HAYES 77) about 100 km southeast of Halifax, N.S. on 18 May 1977 at 1750 ADST.

13. Temperature, dewpoint and C_T^2 profile (FLORIDA 77) south of Panama City, Florida on 19 February 1977 at 1300 CDT. The values of $T_D > T$ are not real but represent a calibration shift of the dewpoint instrument.

FIGURE 1

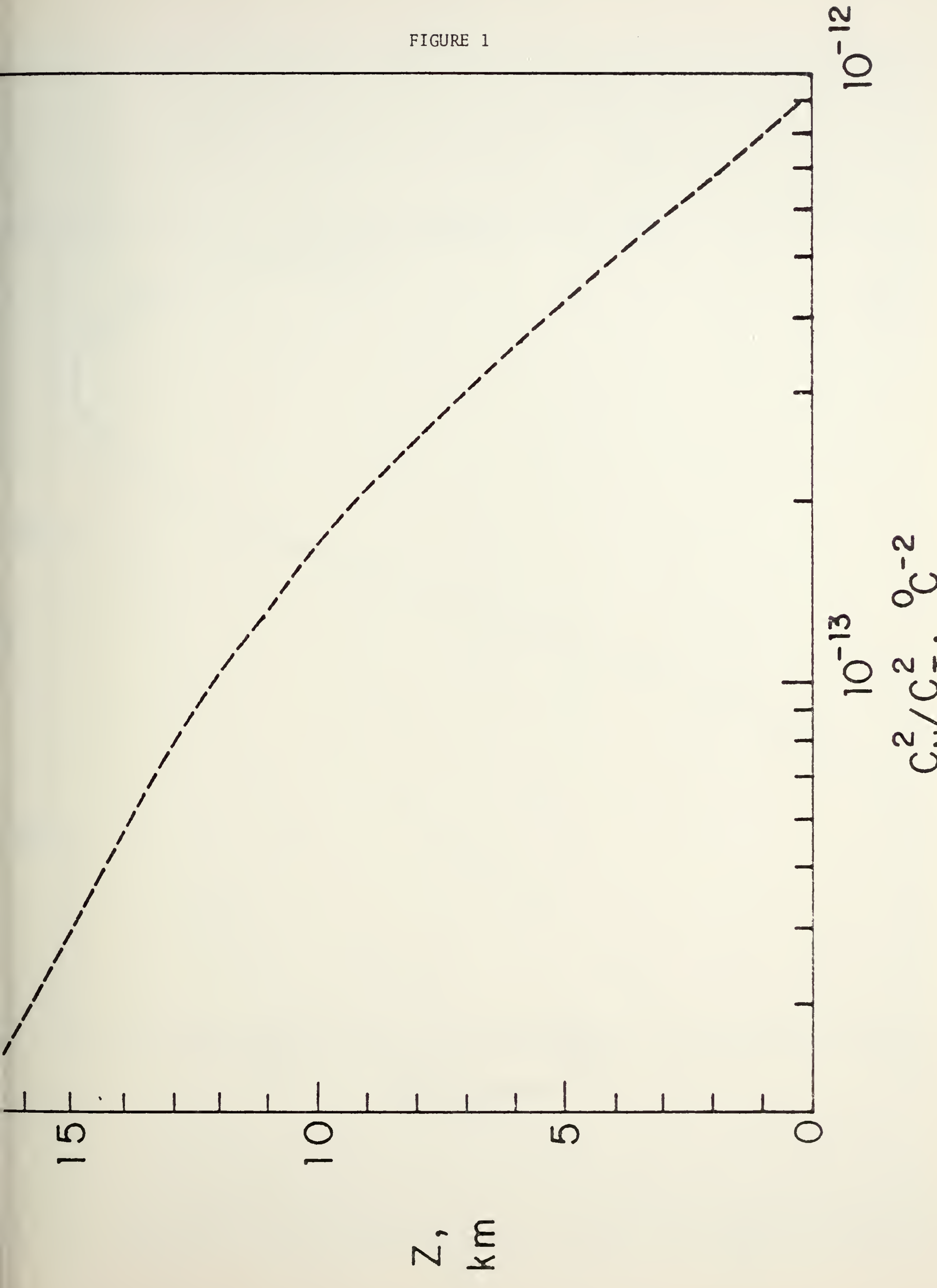
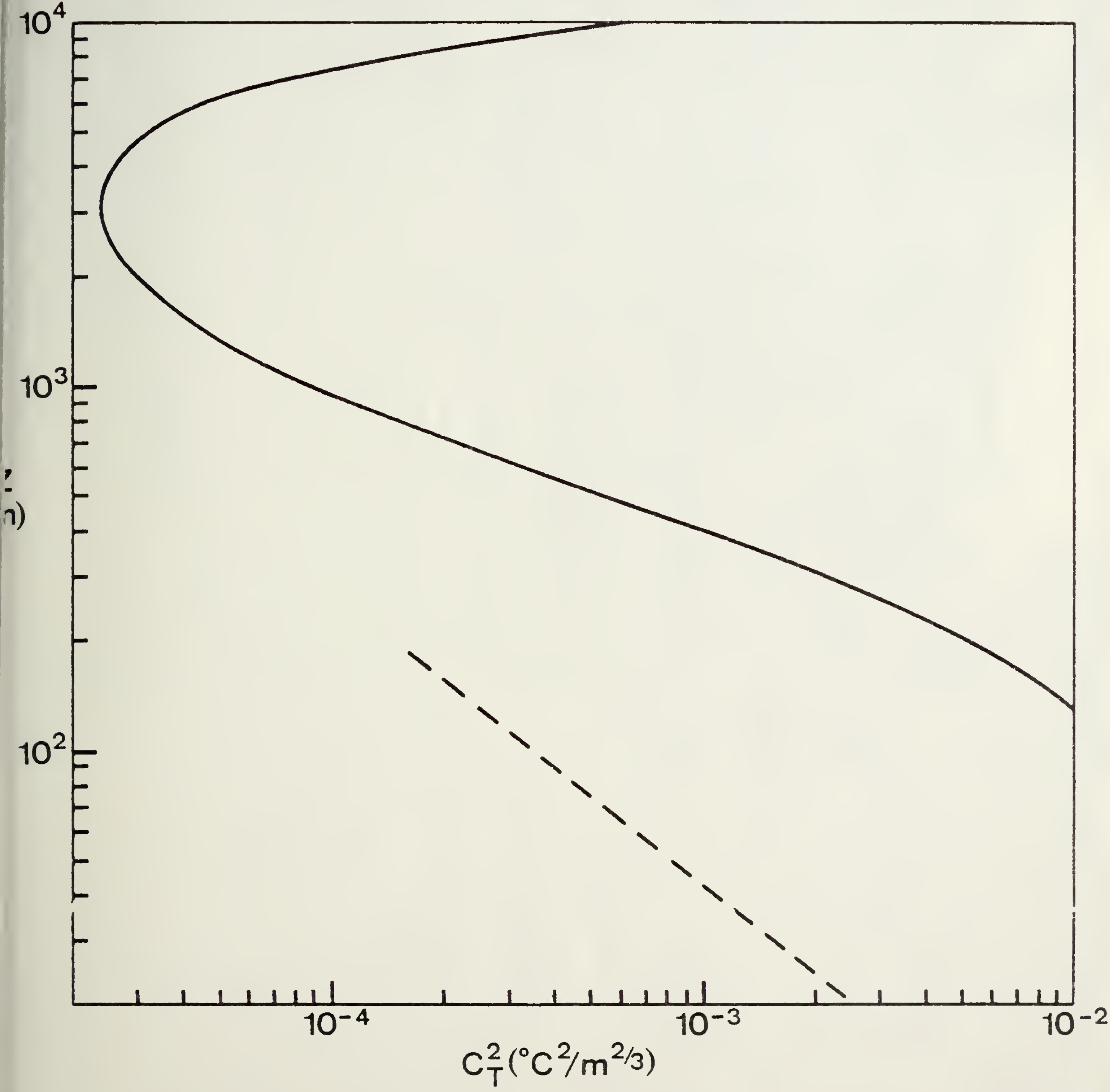


FIGURE 2



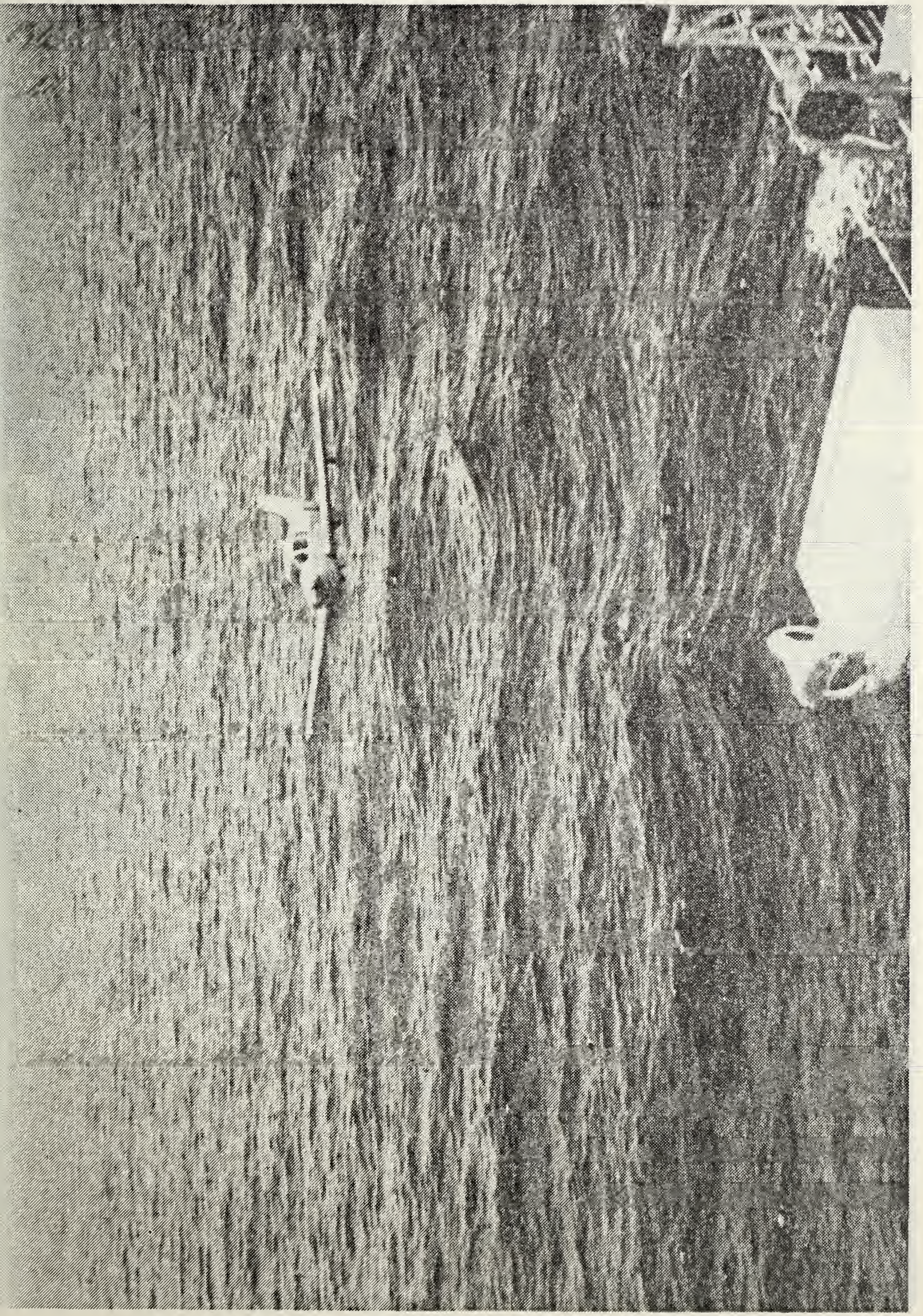
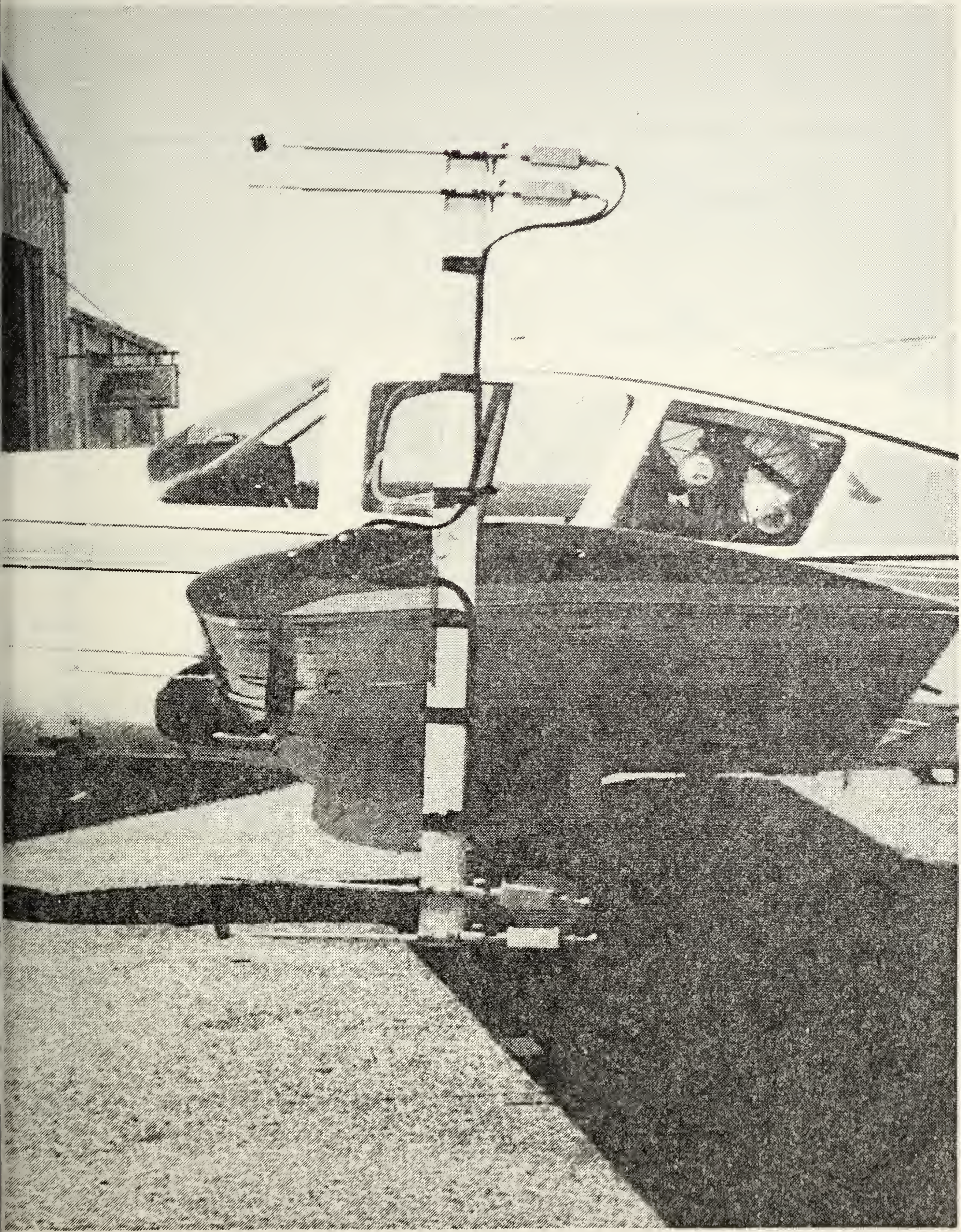


FIGURE 4



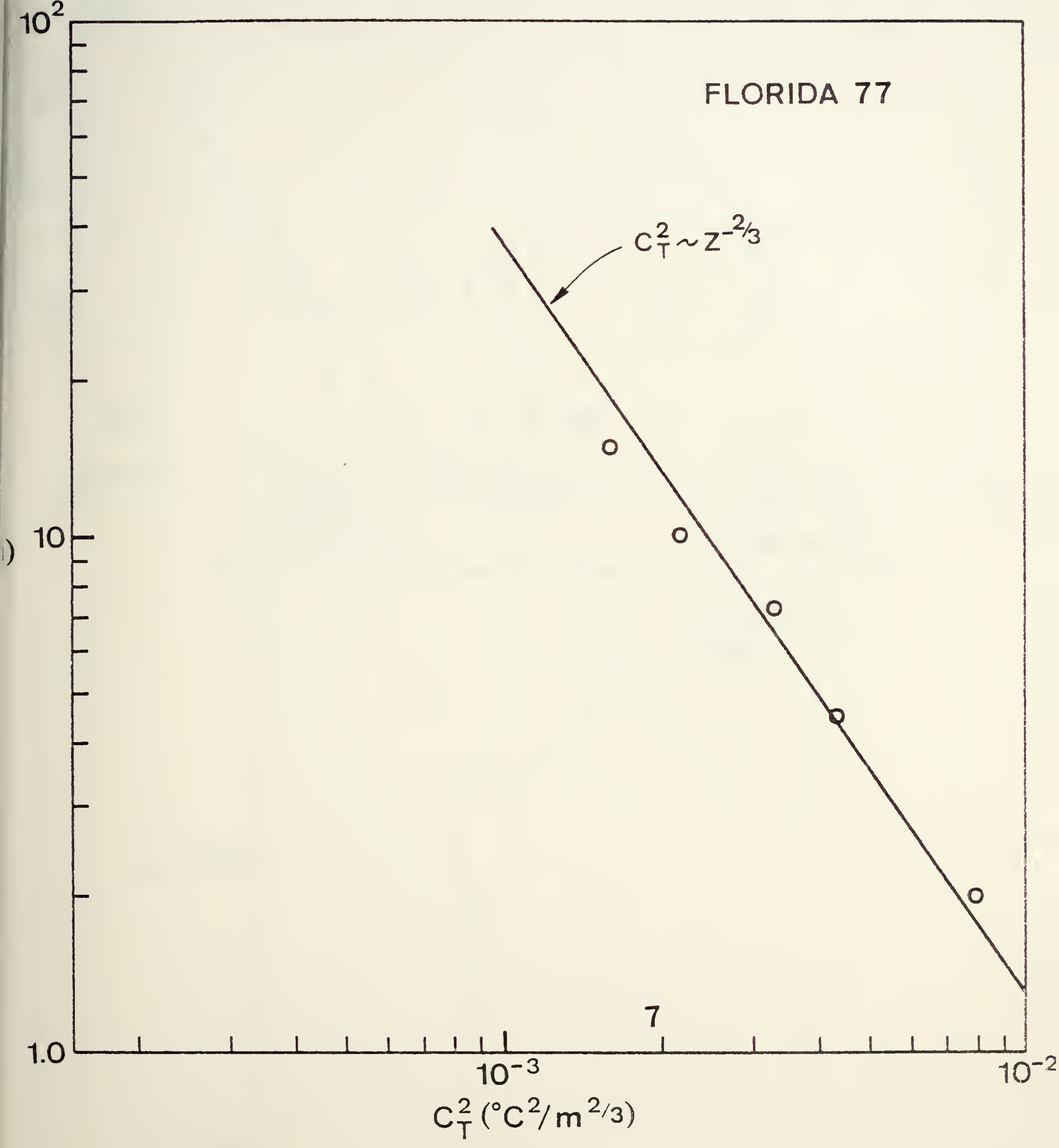
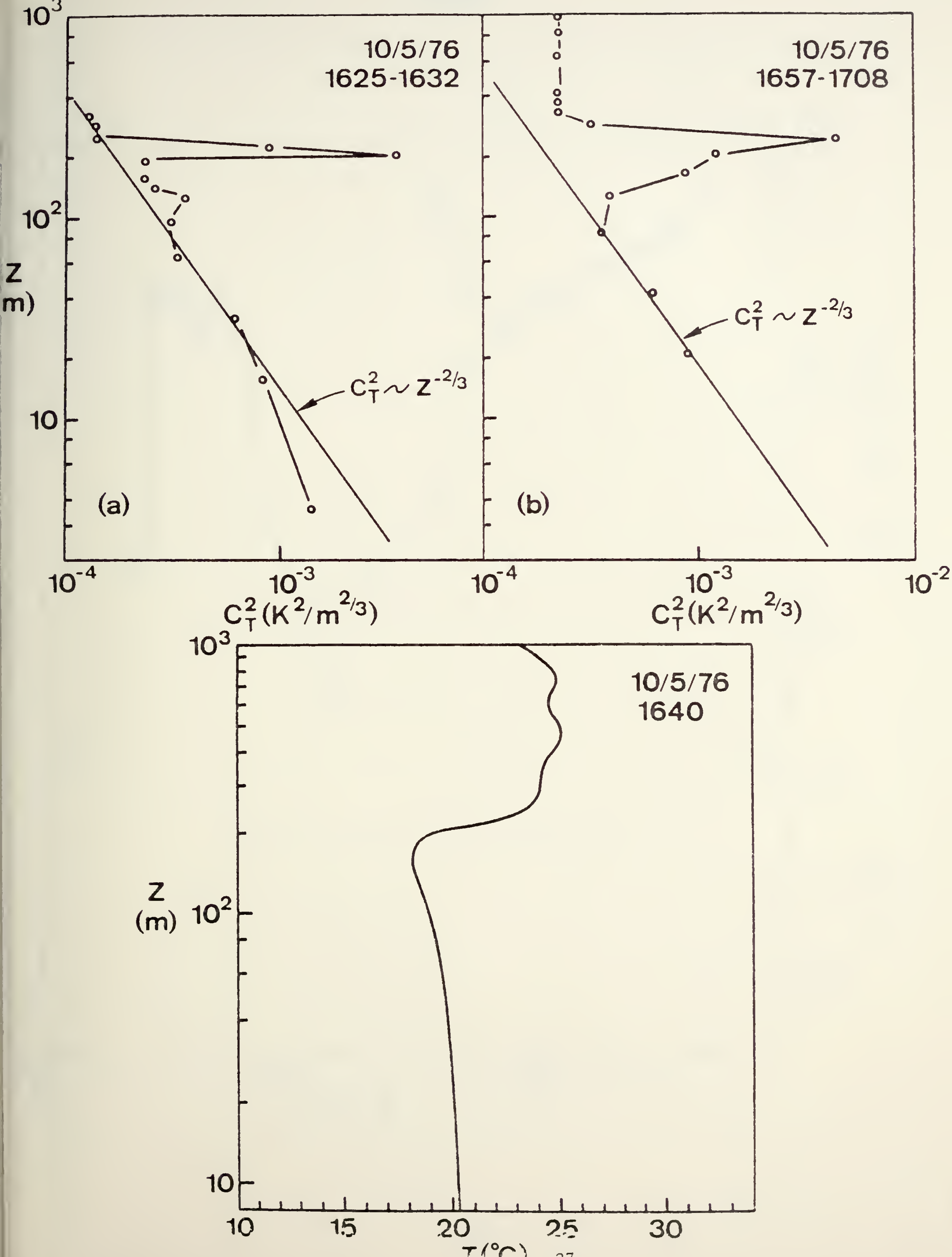

FLORIDA 77
$C_T^2 \sim Z^{-2/3}$
10^2
10
1.0
10^{-3}
10^{-2}
7
C_T^2 (°C^2/m$^{2/3}$)

FIGURE 6



10/5/76
1625-1632
10/5/76
1657-1708
Z
(m)
$C_T^2 \sim Z^{-2/3}$
(a)
(b)
$C_T^2 (K^2/m^{2/3})$
10/5/76
1640
T(°C)

FIGURE 7

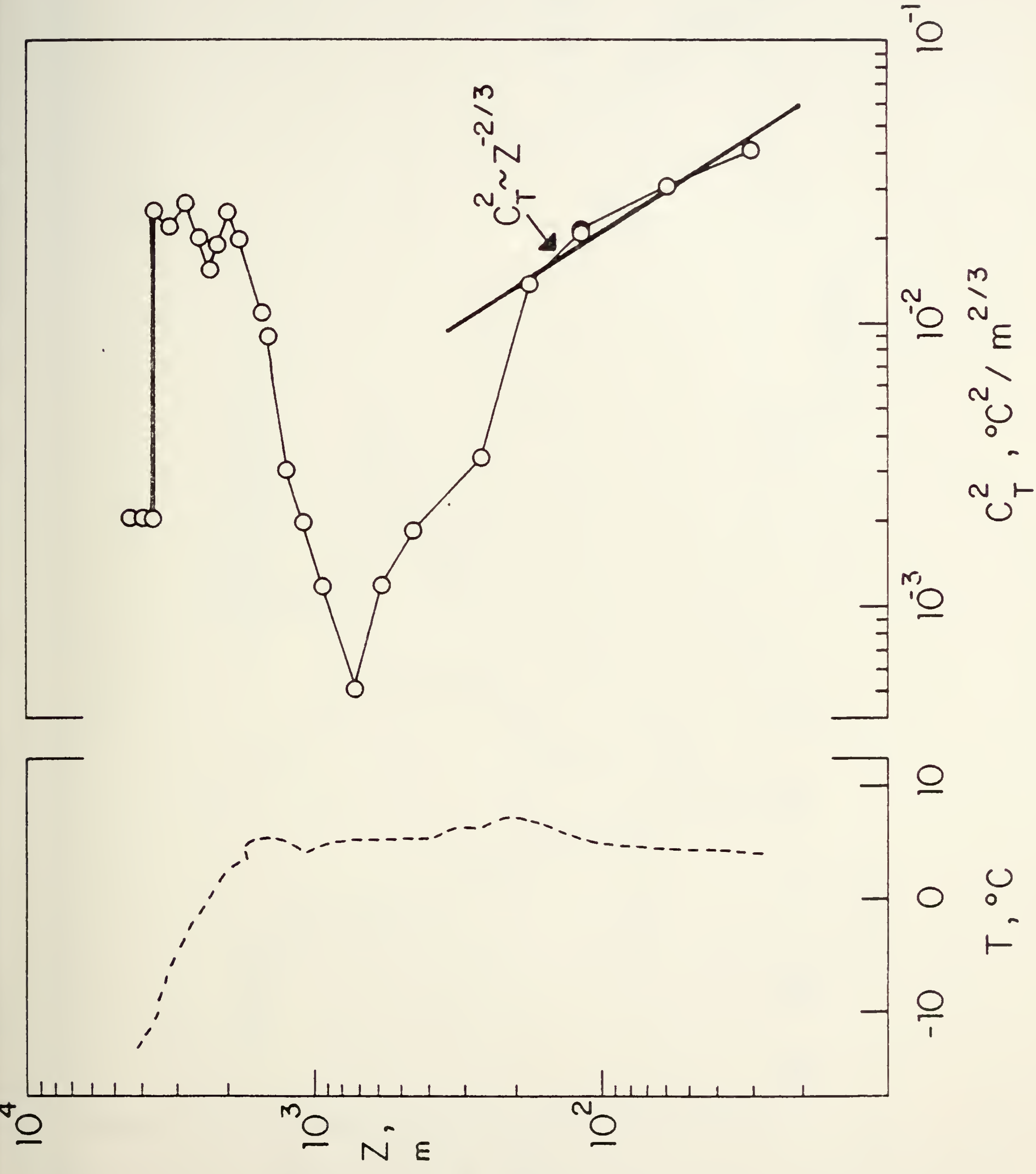
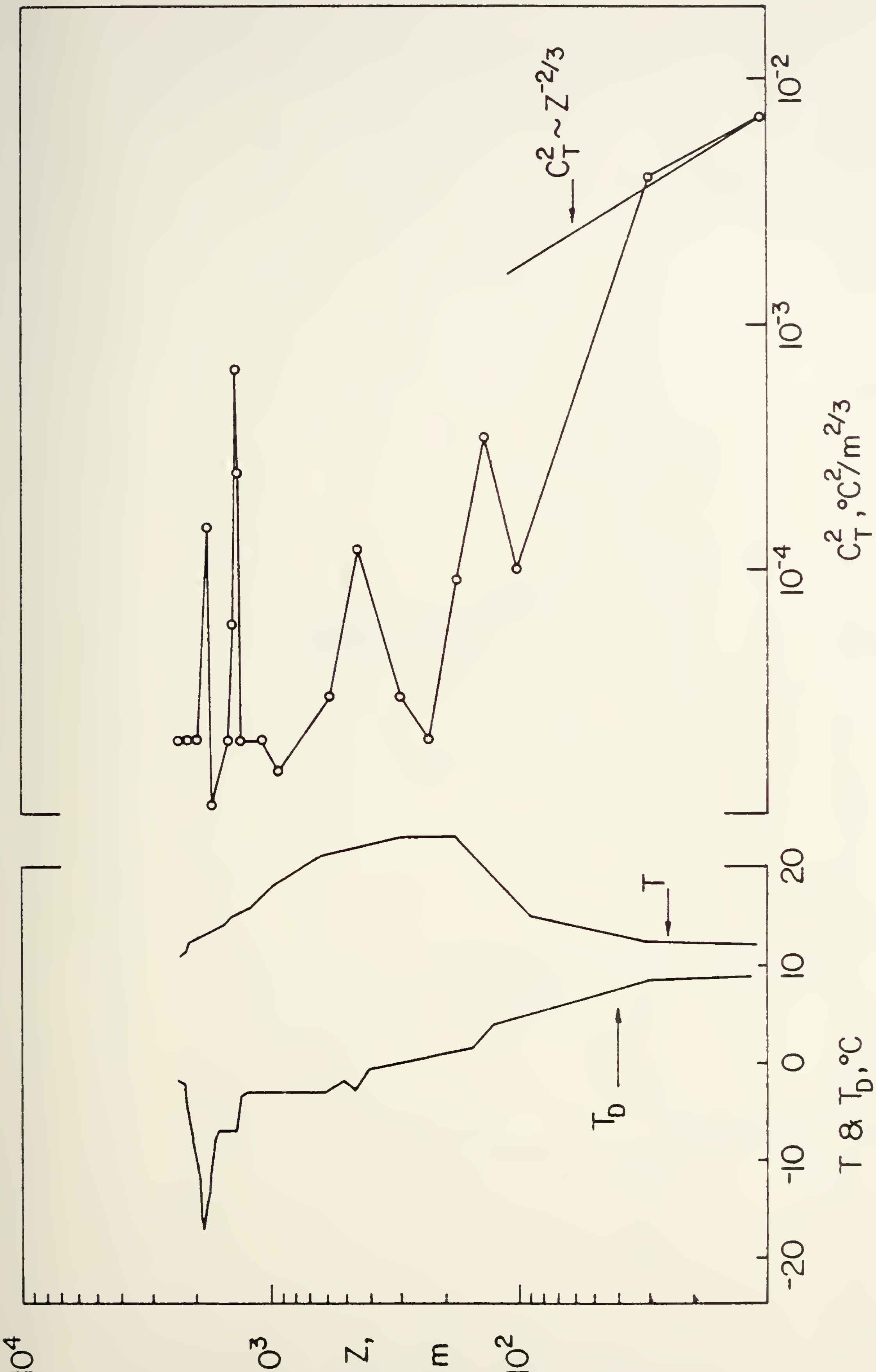


FIGURE 8



$C_T^2 \sim Z^{-2/3}$
10^{-2}
10^{-3}
10^{-4}
C_T^2, °$C^2/m^{2/3}$
T
20
10
0
-10
-20
T_D
T & T_D,°C
10^4
10^3
Z, m
10^2

FIGURE 9

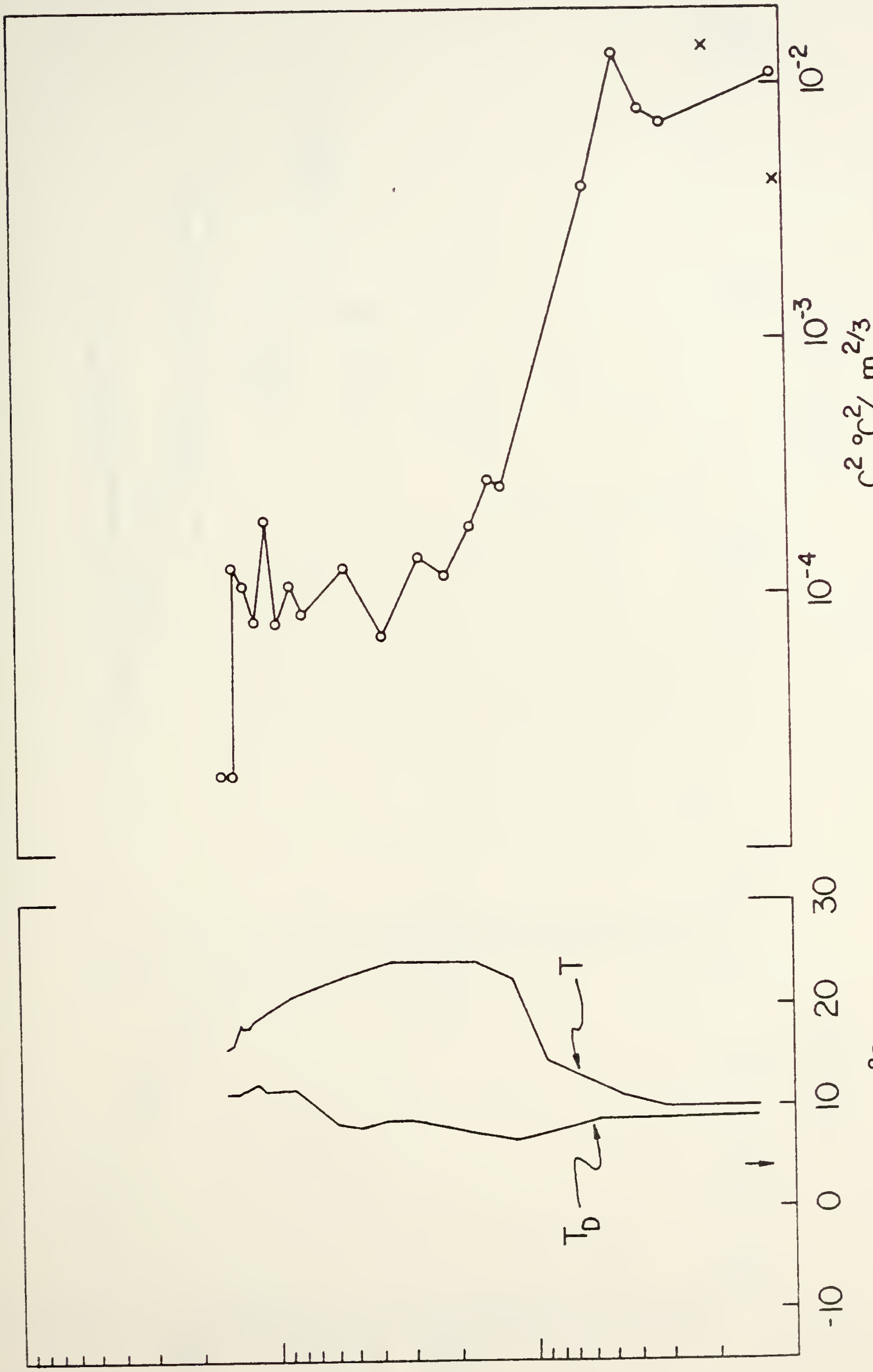


FIGURE 10

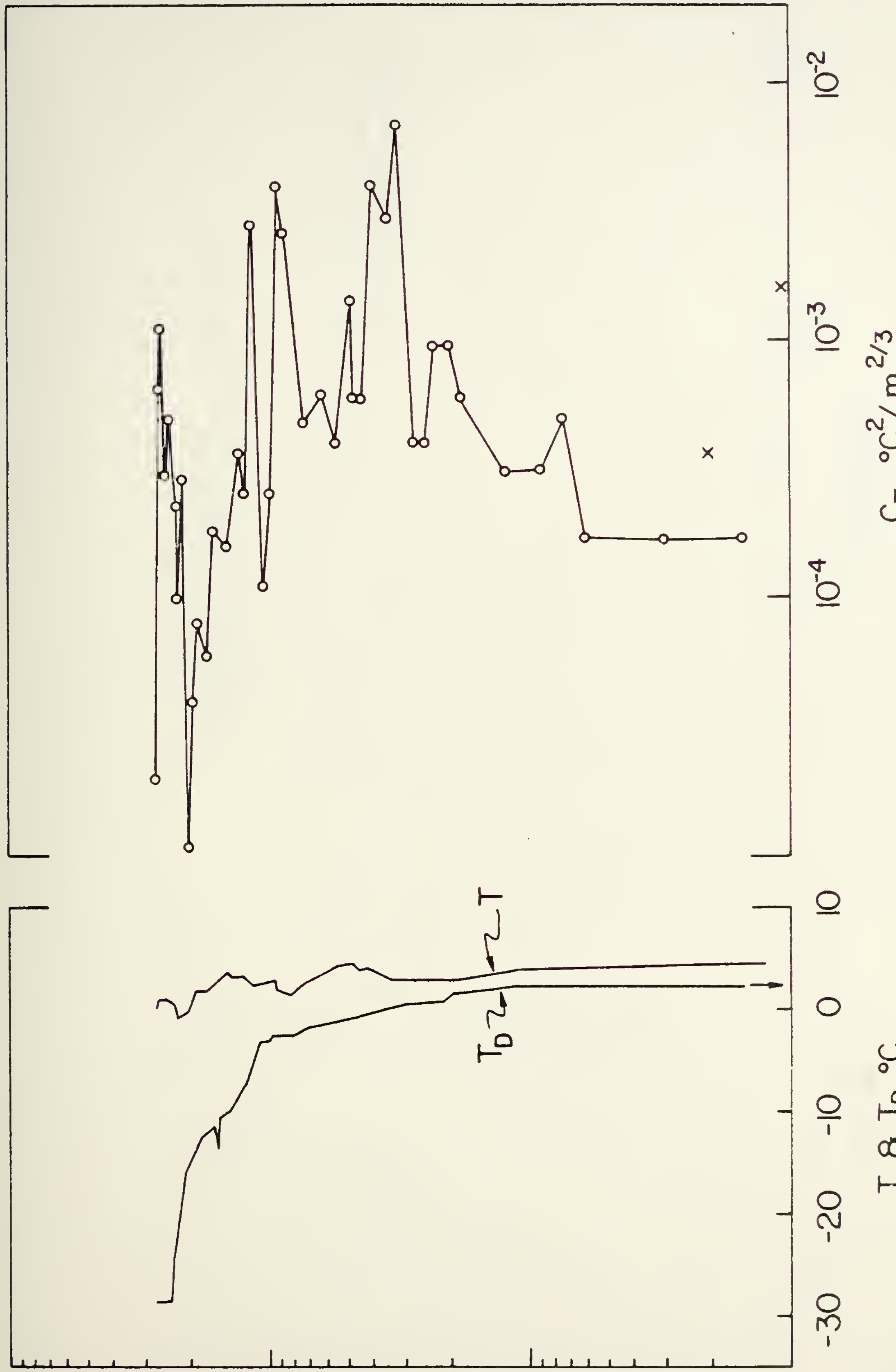
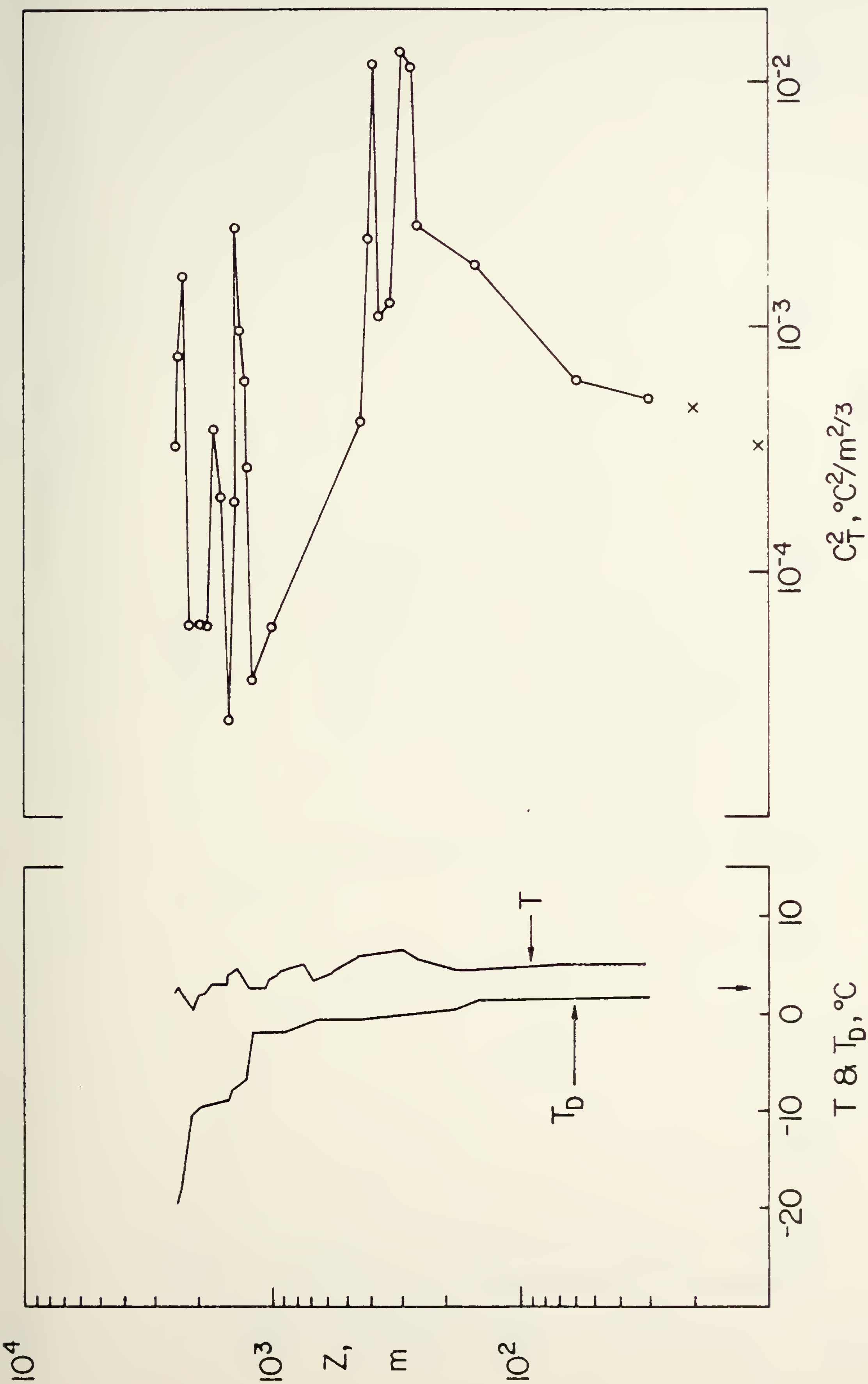


FIGURE 11



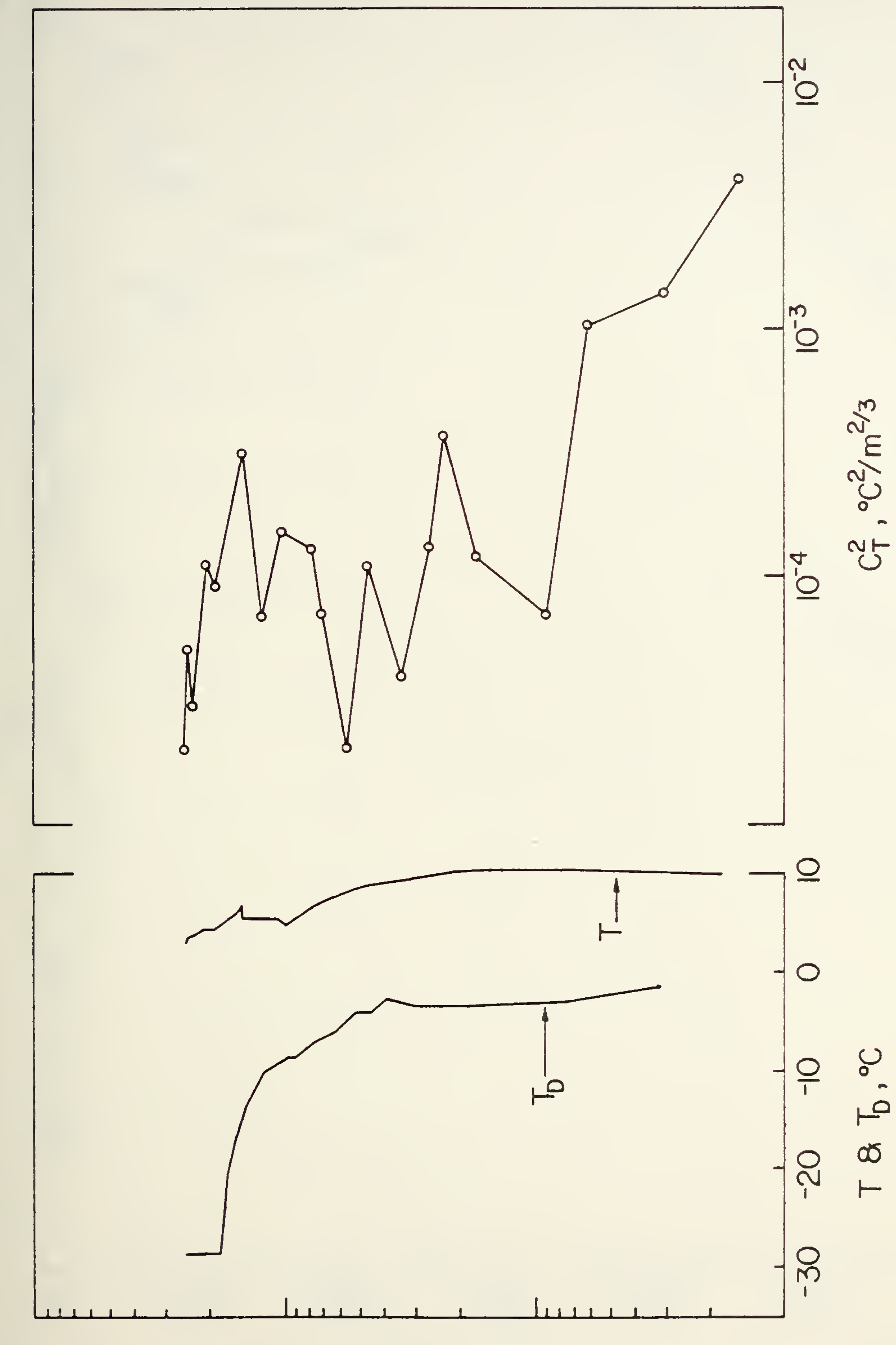
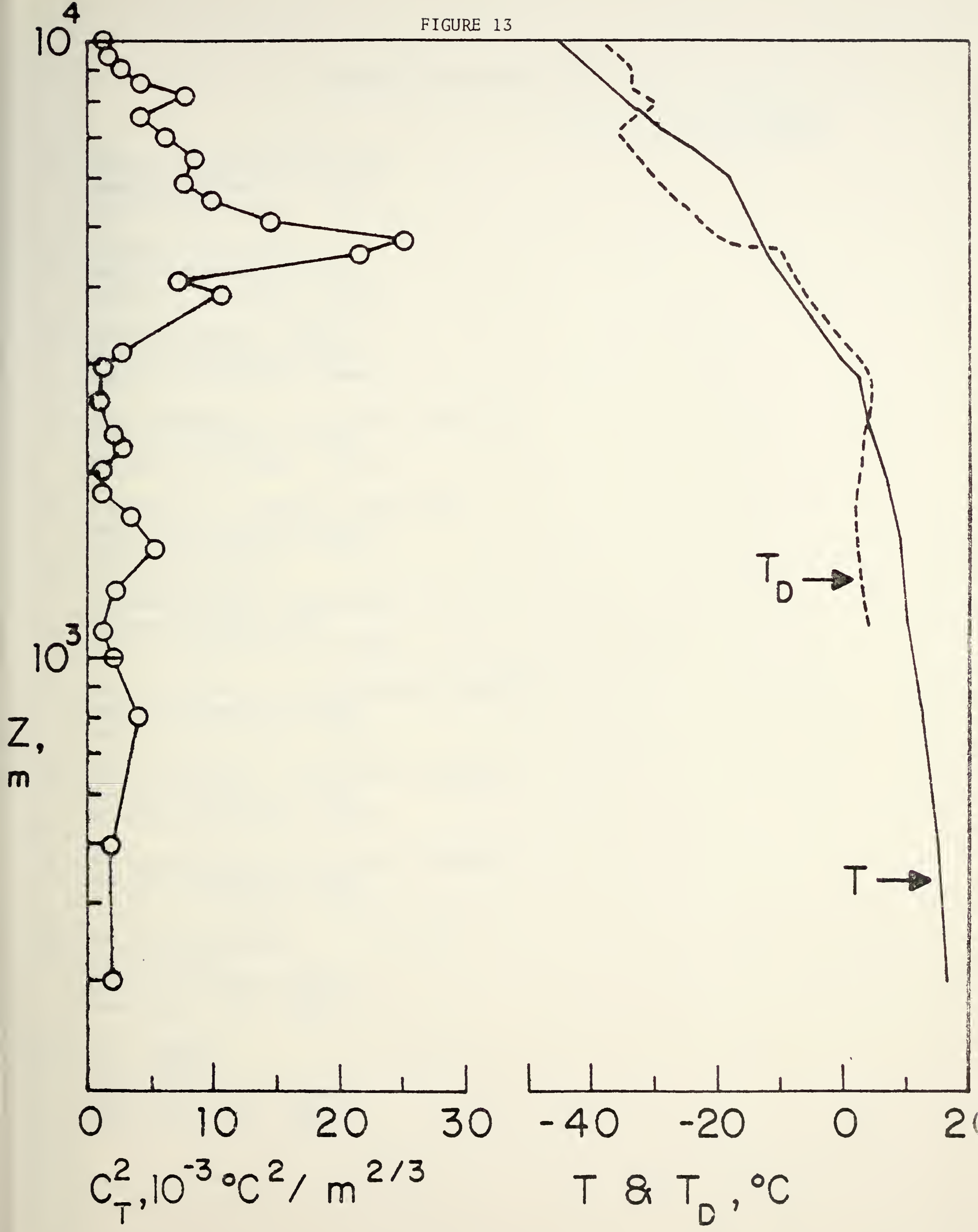

10^4
10^3
Z, m
10^2
-30
-20
-10
0
10
T & T_D, °C
T_D
T
10^-4
10^-3
10^-2
C_T^2, °C^2/m^2/3

FIGURE 13



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